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Radiations from a microstrip travelling wave antenna through lossless warm plasma medium

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Abstract . The radiation performance of a microstrip travelling wave antenna (MSTWA) has been investigated in a warm, lossless, isotropic, electron plasma medium Radiation patterns, radiation resistance, directivity and radiation efficiency expressions are derived and computed in free space as well as in plasma medium by using linearised hydrodynamic equations coupled with vector wave technique Results of a $\lambda/2$ MSTWA are compared with the results obtained for a $\lambda/2$ square patch antenna operating under similar conditions

Keywords Microstrip travelling wave antenna, lossless plasma, radiation resistance

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1. Introduction

Microstrip antennas of different configurations are being increasingly used on board aerospace vehicles, satellites and manportable systems due to their light weight and better aerodynamic properties [1]. These antennas have low gain and bandwidth hence they can't be applied to several applications. A travelling wave antenna like a wire antenna has better gain than other traditional antennas. Considering this fact, the radiation performance of a microstrip travelling wave antenna (MSTWA) is investigated in warm lossless, isotropic electron plasma medium. In travelling wave antenna, fields and current that produce the antenna pattern can be expressed by one or more travelling waves moving in same direction. Since the structure is properly terminated, the reflected waves can be considered small and only a travelling wave distribution can be assumed present. Under such condition, the direction for the radiated beam can be controlled any where between broad side and endfire directions.

Radiating structure, mounted on a space vehicle, intracts with the ionized plasma medium during its voyage through space and radiates electroacoustic waves in addition to usual electromagnetic waves. Presence of these electroacoustic waves is responsible for the change in radiation performance of radiator in plasma medium. Hydrodynamic theory coupled with vector wave technique has been applied to observe the performance of a microstrip travelling wave antenna (MSTWA) in warm electron plasma medium. Initial assumptions and basic equations regarding plasma medium are discussed elsewhere [2]. It is assumed that only aperture portion of antenna encounters the plasma medium and rest of structure is assumed covered by means of a protective layer ($d \leq 1$ mm). The fractional change in resonance frequency due to such covering is found negligibly small (~1%) at 10 GHz which will not cause any serious change in results.

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2. Radiating element

In Figure 1, the conductor patch of a travelling wave antenna of length L is assumed lying in XZ plane and is fed through a coaxial feed line from the back and terminated by a resistive matched load at the other end. It is assumed that it supports only the TE mode. The substrate material ($\varepsilon_r \sim 2.32$) is assumed to be electrically thick (h ~ 0.0095 m) with a substrate permeabi-lity (μ_r) almost equal to unity. The structure can be considered equivalent to two magnetic line sources located at a distance w apart and each source is radiating in the far field region.

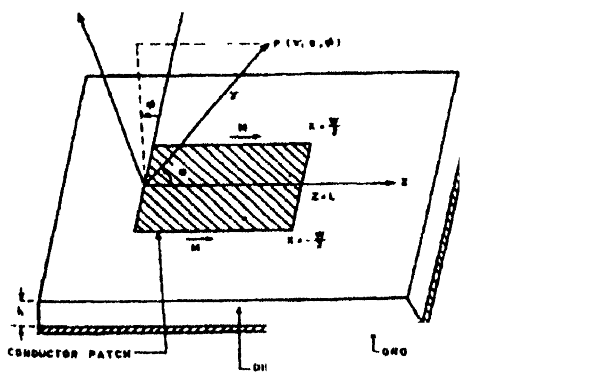

Figure 1. Geometry and coordinate system of a MSTWA

The simple form of magnetic line source is considered as

$$M(z) = M_0 \hat{z} e^{-j\gamma z}$$
$$- 2 E_0 h \hat{z} e^{-j\gamma z}$$

For better interpretation, γ is expressed as $(\gamma = \beta - j\alpha)$ because it does not affect the general form of the above equation. The final expression for γ (a real quantity) used for calculations, has the form

$$\gamma = \left[(\pi^2 / h^2) - \frac{4\pi^2}{\lambda^2}\varepsilon r\right]^{1/2}.$$

The H-plane far field radiation pattern factor $R(\theta, \phi)$ for EM mode and EP mode are evaluated for different lengths ($L = a\lambda_0$) of radiating structure for different plasma to source frequencies (ω_p/ω). Here a is a positive real number. The expressions are :

EM Mode

$$R(\theta,\phi)_E = |E_\theta|^2 + |E_\phi|^2$$

$$= \left\{\frac{\beta_e M_0 L h}{2\pi r}\frac{\sin[(L/2)(\beta_e \cos\theta - \gamma)]}{[(L/2)(\beta_e \cos\theta - \gamma)]} \times \sin\theta\right.$$

$$\times \cos[(\beta_e(w/2)\sin\theta\cos\theta]\frac{\sin[\beta_e(h/2)\sin\theta\sin\phi]}{[\beta_e(h/2)\sin\theta\sin\phi]}$$

EP Mode

$$R(\theta,\phi)_P = |E_p|$$

$$\frac{60\sqrt{\varepsilon_r}}{\gamma h(C/v_0)}\left(\frac{1-A^2}{A}\right)\frac{\sin[(L/2)(\beta_p \cos\theta - \gamma 0]}{[(L/2)(\beta_p \cos\theta - \gamma 0]}$$

$$\times \cos[\beta_p(w/2)\sin\theta\cos\phi] \times \frac{\sin[(\beta_e(h/2)\sin\theta\sin\phi]}{(\beta_e(h/2)\sin\theta\sin\phi)}\Bigg]^2$$

with $\beta_p = \frac{C}{\ }\quad \beta_e = \left|\frac{C}{\ }\right|\beta_0 A$.

β_e and β_p are propagation constants in EM and EP modes respectively. η is free space wave impedance = 377 Ω. For present communication, three values of a (a = 5, 10 and 20) are selected. $A = \sqrt{1-(\omega_p^2/\omega^2)}$ is the plasma parameter $C/v_0 = 10^3$ where C is the velocity of the light while v_0 is the r.m.s. thermal velocity of electrons.

3. Results and discussion

The H-plane radiation patterns in EM mode for MSTWA are shown in Figure 2 in free space as well as in plasma medium for two values of plasma parameter A [A = 1.0 (free space), 0.5].

The curves indicate the presence of a prominent main lobe followed by a number of side lobes. The intensity of radiations, distributed inside lobes is sufficiently high in the plasma medium and hence radiation intensity directed towards the main lobe decreases considerably. As shown in Table 1, on increasing plasma to source frequency, the 3 db beam width of main lobe increases and hence the directive gain of radiator decreases. Similarly on increasing the length of the radiator, 3 db beam width of main lobe decreases which in turn increases the directivity of radiator.

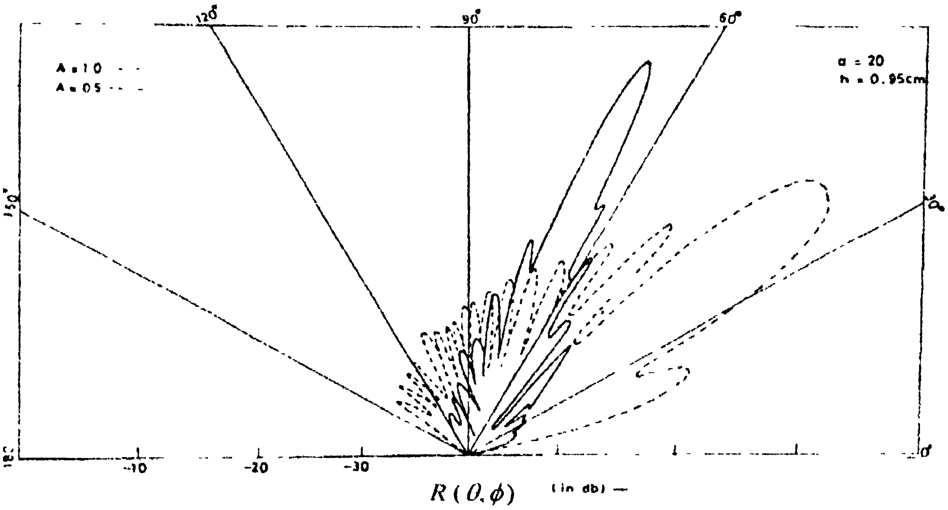

Figure 2. H-plane radiation patterns of MSTWA for A = 1.0 and A = 0.5

Table 1. 3 db beamwidth of MSTWA in plasma medium

Sl No	Plasma parameter $A = \sqrt{1-(\omega_p^2/\omega^2)}$	3 db beam width $L = 5\lambda$	$L = 10\lambda$	$L = 20\lambda$
	1.0	11°	4°	
	0.5	26°	16°	

The EP mode radiation patterns have a discrete ray like structure comprising of innumerable maximas and minimas These patterns are similar to other microstrip antennas [3] and are not reported in the present communication.

For better understanding, H-plane field patterns of a microstrip travelling wave antenna and a microstrip square patch radiator; both having half wave length ($\lambda/2$) dimensions are compared. For all plasma to source frequency ratios, the maximum intensity for a square patch radiator is found in the direction normal to patch ($\theta = 90°$). However, for a $\lambda/2$ microstrip travelling wave radiator as shown in Table 2, the main lobe inclined in $\theta = 58°$ starts shifting towards the XY plane ($\theta = 90°$ direction) on increasing the plasma to source frequency. Ultimately for ω_p/ω - 0.994 (A - 1) the main lobe attains $\theta = 90°$ direction, though the radiation intensity is found sufficiently smaller than that in free space (ω_p/ω - 0).

Table 2. Effect of plasma medium on the direction of maximum intensity of a MSTWA and a $\lambda/2$ square patch antenna

Sl No	Plasma parameter	Direction of maximum intensity (θ)	
	A	$\lambda/2$ Square patch antenna	$\lambda/2$ MSTWA
1	0 1	90°	90°
2	0 3	90°	86°
3	0 5	90°	82°
4	0 7	90°	74°
5	0 9	90°	62°
6	1 0	90°	58°

The radiation resistance $\left[R_{\rm rad} = \frac{V_0^2}{P_{\rm rad}} = \frac{4h^2E_0^2}{P_{\rm rad}}\right]$ of a MSTWA in EM mode shown in Figure 3, initially decreases on increasing plasma to source frequency. Here V_0 is the voltage across the slot which is invariant over its width. However, on increasing ω_p/ω further, radiation resistance starts decreasing quickly. Similar behaviour is recorded for a $\lambda/2$ travelling wave antenna operating under similar conditions. It has been observed that this behaviour do not match with the behaviour of same structure built on a thin substrate (h - 0 0016 m) material. In this case, radiation resistance is minimum in free space (~619 Ω for a - 5 and 151 Ω for a - 20) and increases rapidly on increasing ω_p/ω value. However, this behaviour agree well with the trend of radiation resistance for a square patch radiator operating under similar conditions. The plasma mode radiated power is zero in free space (A = 1.0) and hence the radiation resistance decreases on increasing plasma to source frequency for both thin and thick substrates.

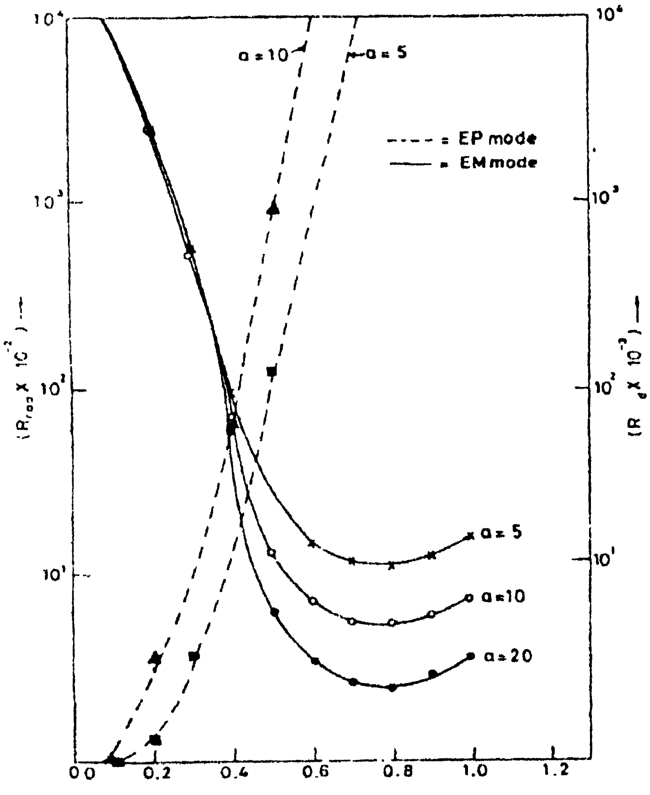

Figure 3. EM and EP mode radiation resistance of a MSTWA

The radiation efficiency in plasma medium

$$\eta = \left[P_e / (P_e + P_p)\right] \times 100\%$$

indicates that for a long travelling wave antenna as shown in Figure 4, it is close to 100% even when ω_p/ω is changed from 0 to 0.86 but later it starts decreasing. However for a $\lambda/2$ MSTWA, radiation efficiency continuously decreases on increasing plasma to source frequency. This behaviour is similar to the behaviour of a $\lambda/2$ long rectangular patch antenna reported earlier [4].

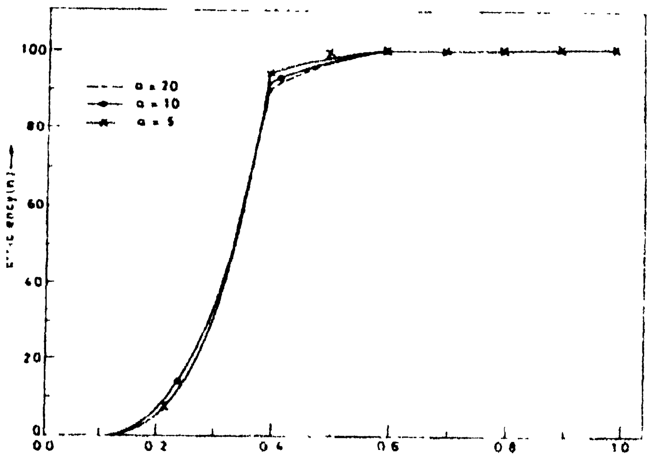

Figure 4. Efficiency of MSTWA in plasma medium

The directivity and radiation efficiency of a $\lambda/2$ MSTW radiator is however large than the corresponding values for a square patch antenna operating under similar environmental conditions.

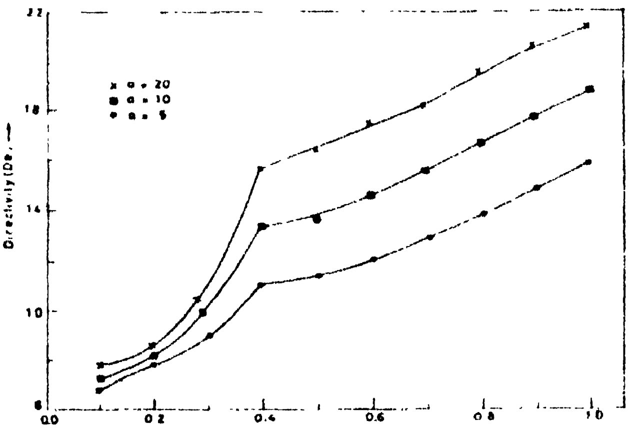

Figure 5. EM mode directivity for different plasma parameter (A) values

The behaviour of directivity (De) with plasma parameter A is shown in Figure 5. In every case, directivity is maximum in free space ($A = 1$) and decreases on increasing ω_p/ω value. A longer line displays more directive behaviour than a shorter line. Similar conclusion is reported earlier when 3 db beamwidth is reported.

It can be concluded from the present observations that a long microstrip travelling wave radiator (length equal to several wave lengths) with appropriate dielectric constant and substrate thickness will suit better than other radiators for application through plasma medium particularly when main beam in a particular direction (beam scanning) is needed. This conclusion needs experimental support but simulation of natural plasma medium in lab is very difficult to achieve.

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